Korea Astronomy and Space Science Institute

THE UNIVERSITY OF ARIZONA
COLLEGE OF SCIENCE
Astronomy & Steward Observatory

MNRAS, 513, 1, pp.1459-1487,
arXiv:2203.07675

Meeting new challenges in low surface-brightness astronomy with the next generation of cosmological simulations

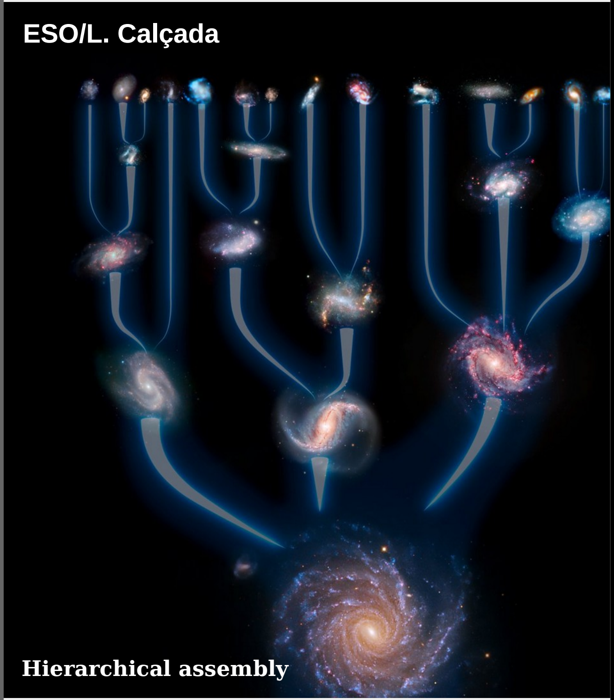
Garreth Martin
with
LSST Galaxies LSB Working Group

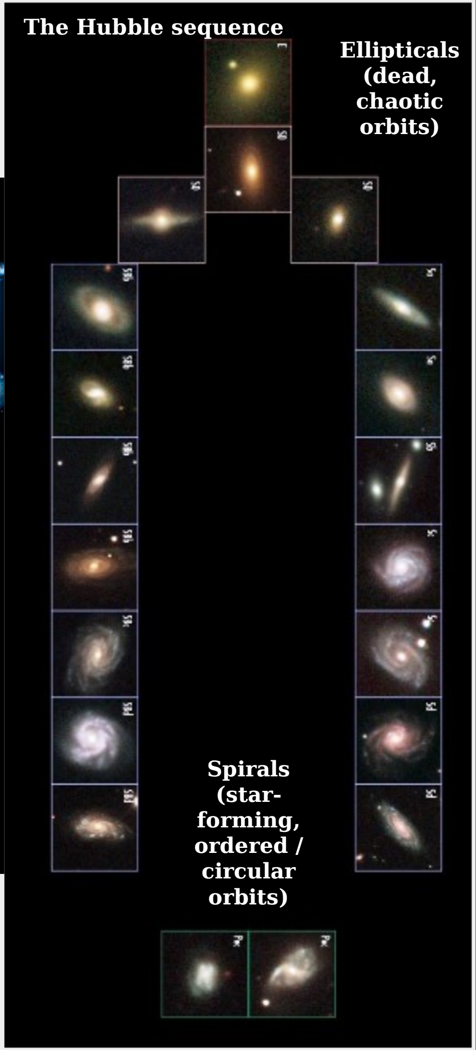
KIAS Survey Science Workshop, 경주 , *2023-01-16*

Mergers leave signatures in the tidal debris surrounding galaxies.

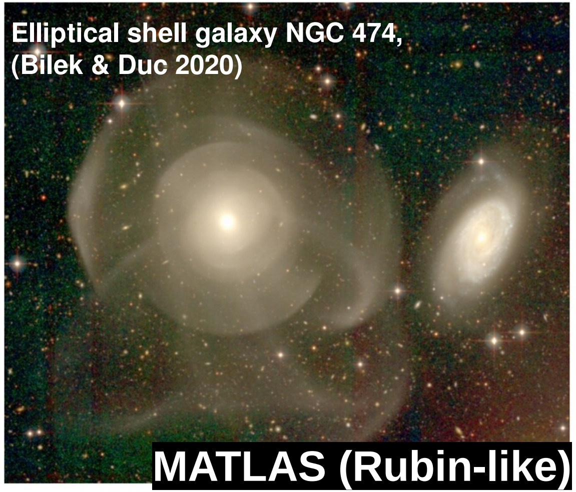
Studying these in detail over cosmic time will allow us to reconstruct how structure in the universe has evolved over its lifetime.

And understand how the diversity of galaxy morphology in the present-day Universe emerged.



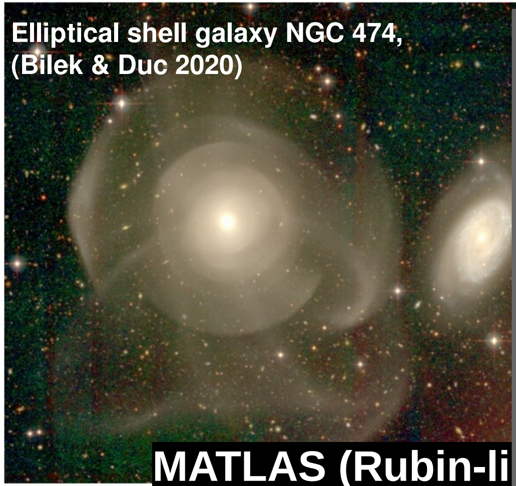


Past surveys



Current state-of-the-art

Past surveys

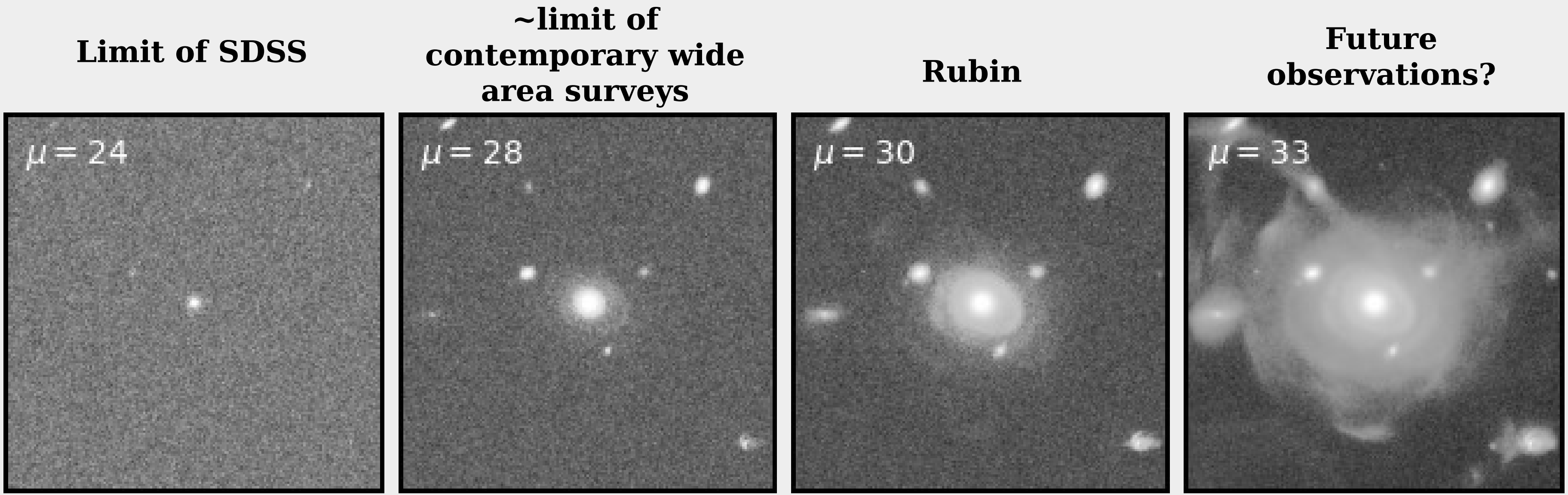


Current state-of-the-art

Past astronomical surveys (like SDSS) are only sensitive enough to probe the central parts of galaxies, leaving a significant gap in our knowledge.

With deeper imaging, galaxies reveal intricate structures in their outskirts which are powerful indicators of the processes that drove their evolution.

Unlike current deep surveys, which typically image 10-100 galaxies, <u>Rubin will produce deep observations for billions of galaxies</u> ($\mu^{lim}_{r}(3\sigma, 10'' \times 10'') > 30.5$ mag arcsec^{-2}).



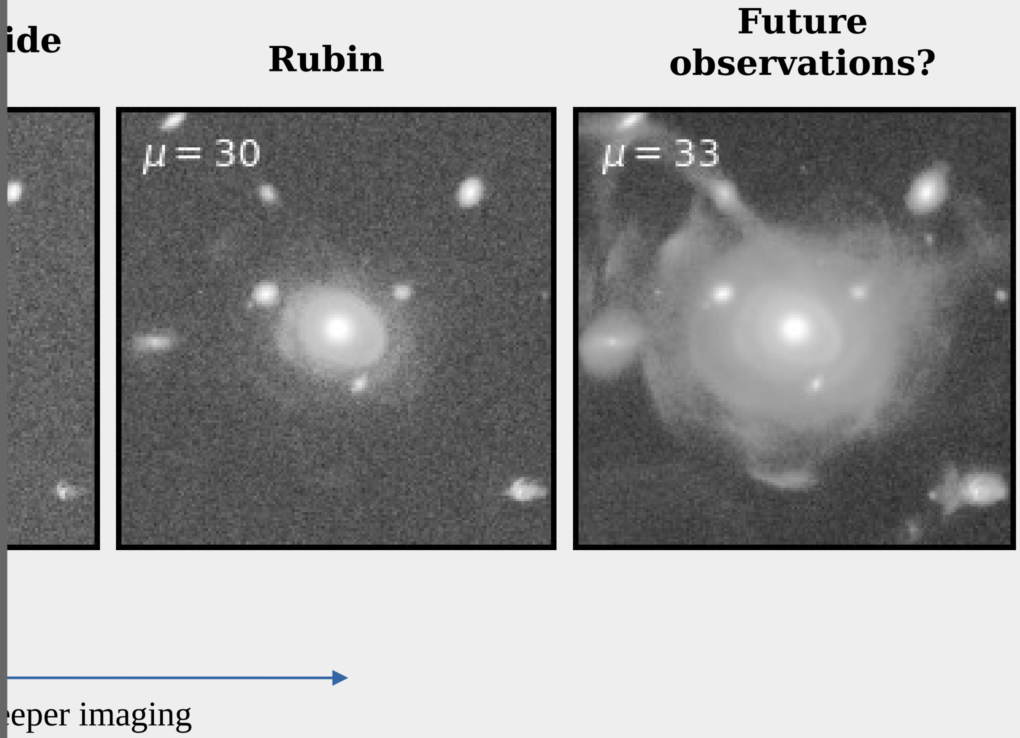
Synthetic images

Deeper imaging

Martin+ in prep

Using cosmological simulations we can produce self-consistent ΛCDM predictions for the outer region of galaxy stellar haloes.

By digging deeper into galaxy haloes, we reveal increasingly complex and intricate structure, encoding billions of years of cosmic history.



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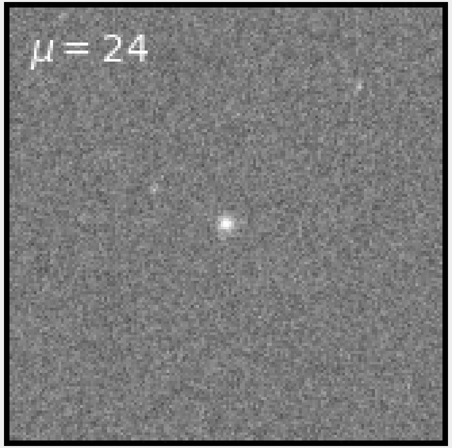
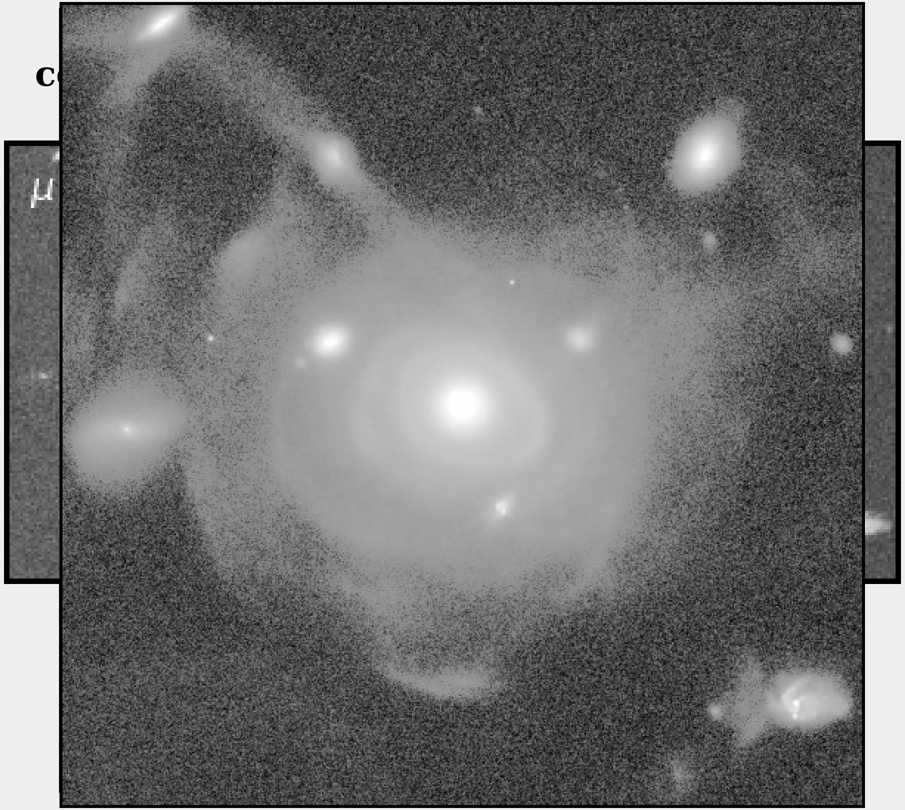
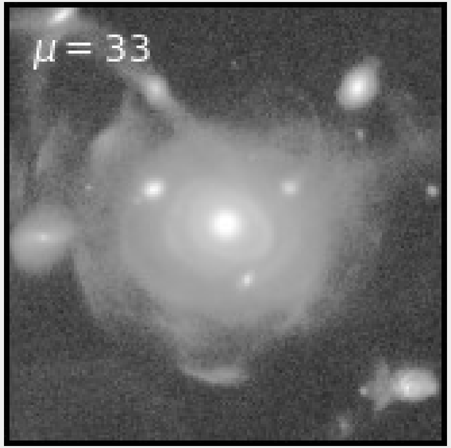
Limit of SDSS





Future observations?



Synthetic images

Martin+ in prep

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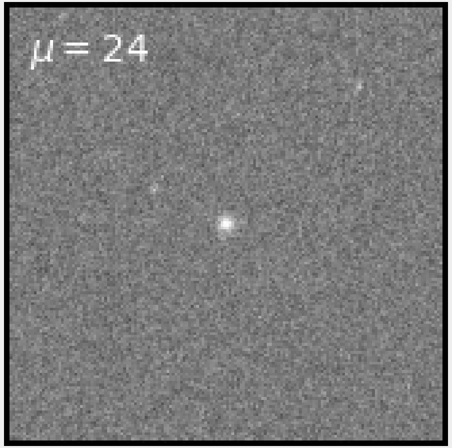

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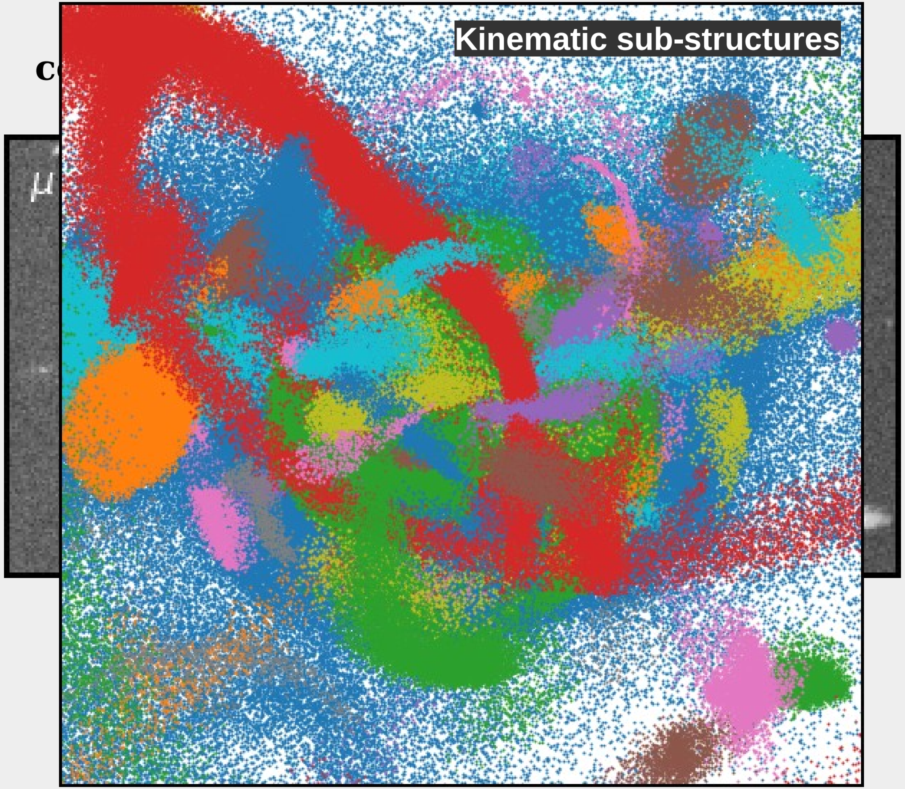

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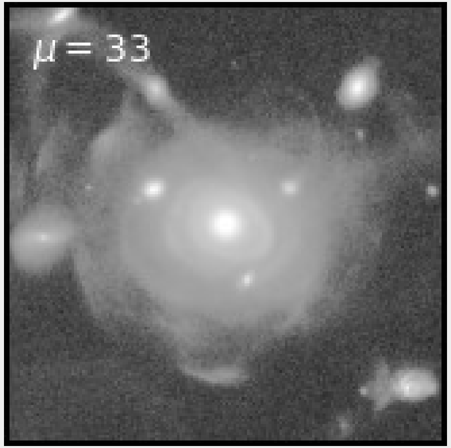
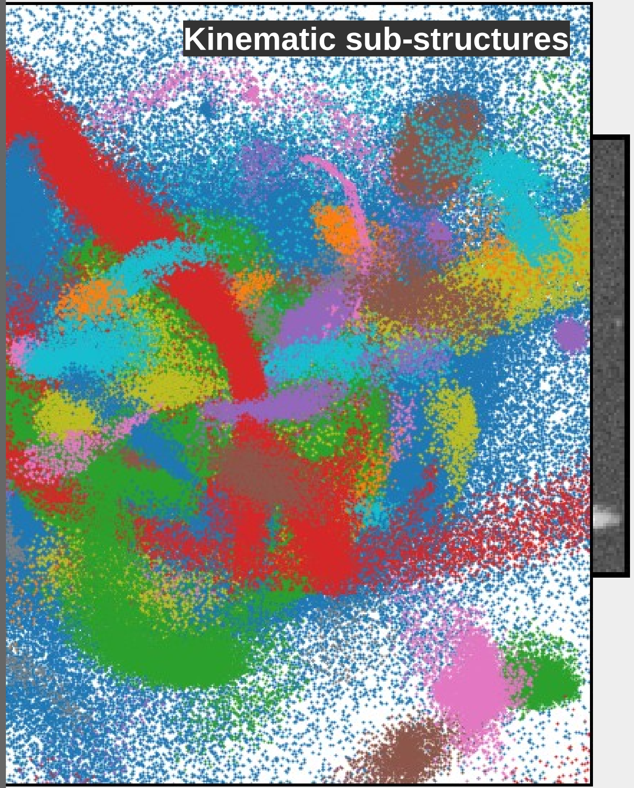
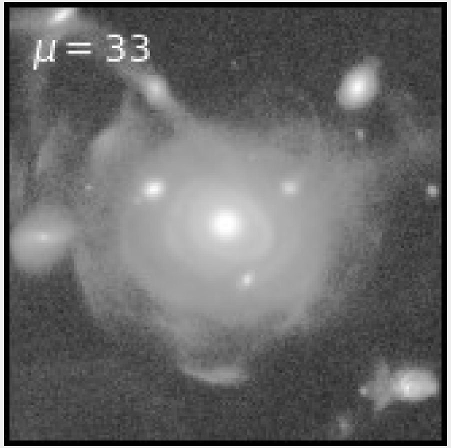


Tidal sub-structure allow us to access <u>a uniquely detailed record of how each galaxy has evolved over cosmic time.</u>

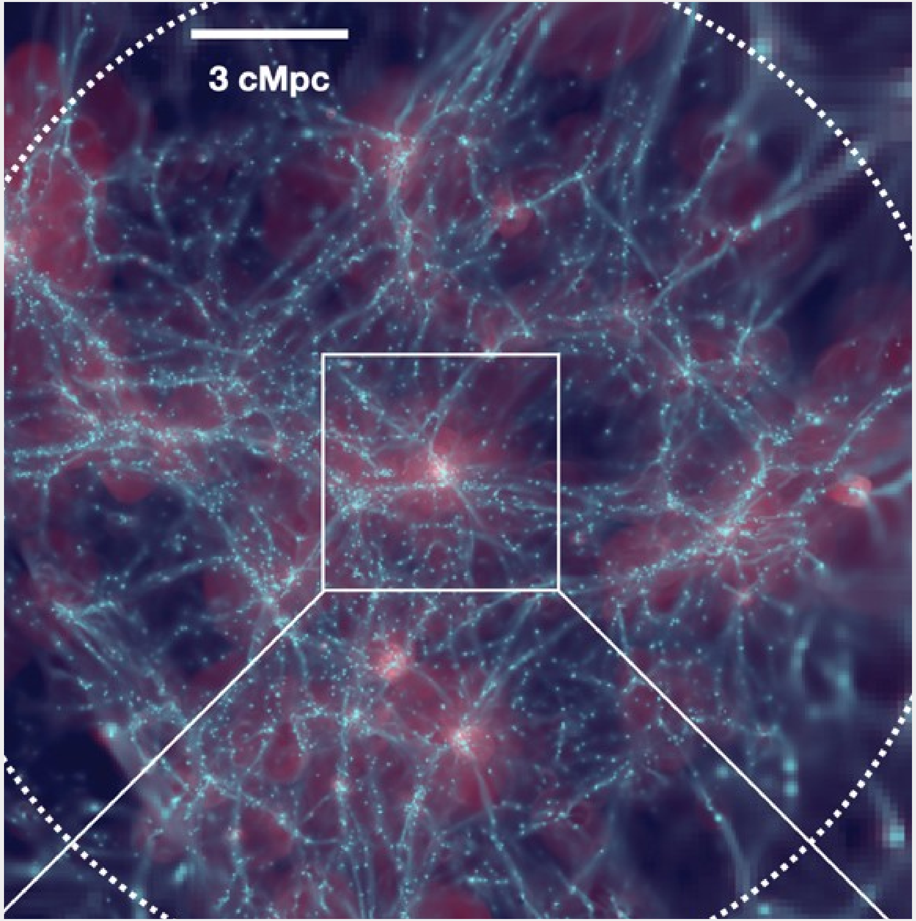
By performing a census of the assembly histories of present day galaxies, we can understand how the diversity of galaxy morphology and properties in the present-day Universe emerged.



Future observations?



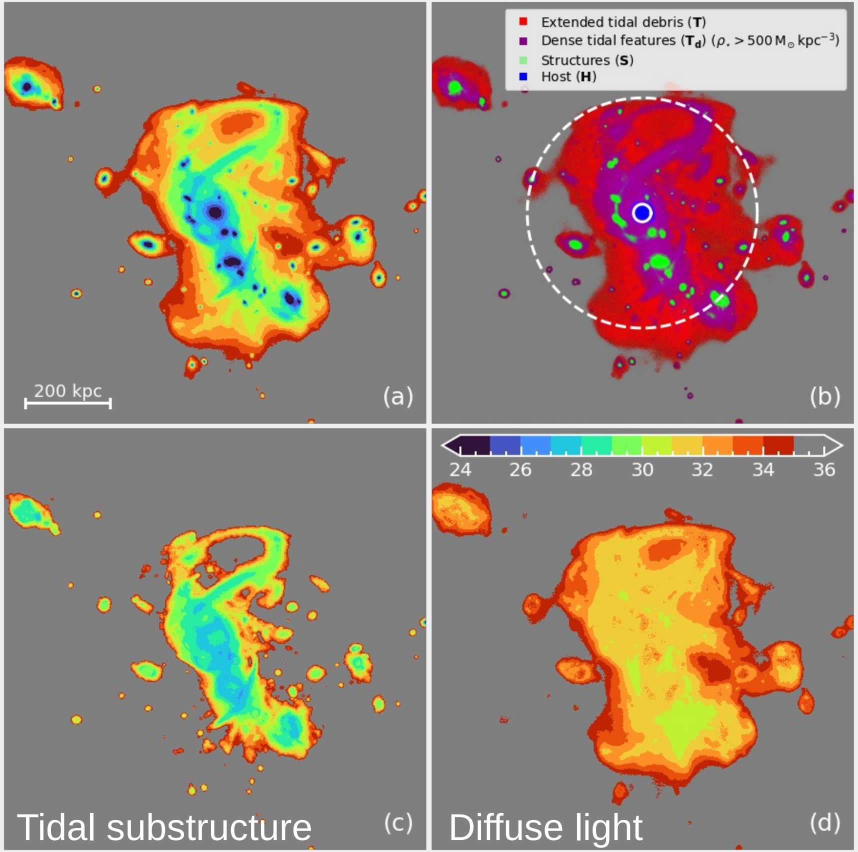
Dubois+2021, A&A, 513, 1, pp.29, arXiv:2009.10578



Predictions for the LSST survey from the NewHorizon cosmological simulation

Martin+2022, MNRAS, 513, 1, pp.1459-1487, arXiv:2203.07675

Measuring flux distributions in the stellar halo



- Decompose galaxy stellar haloes into:
  1) Dense tidal substructures (density cut maximising high spatial frequency features <50 kpc **Sola+2022**)
  2) Diffuse light / debris (low spatial frequency features)

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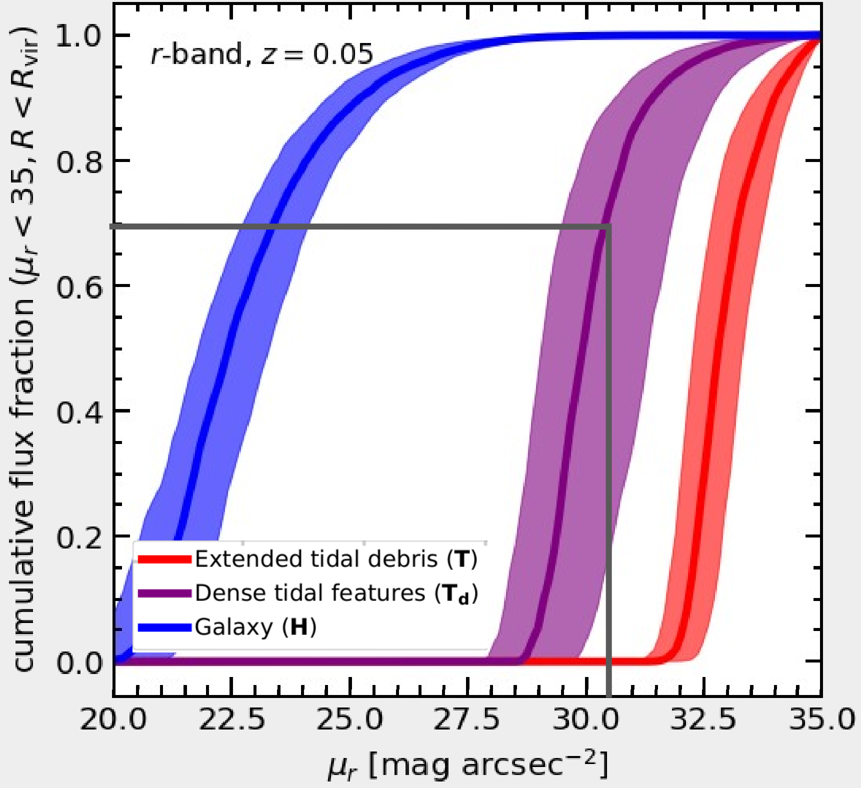

- SB limit of 30.5 mag / sq. arcsec is sufficient to recover over half the flux within tidal features

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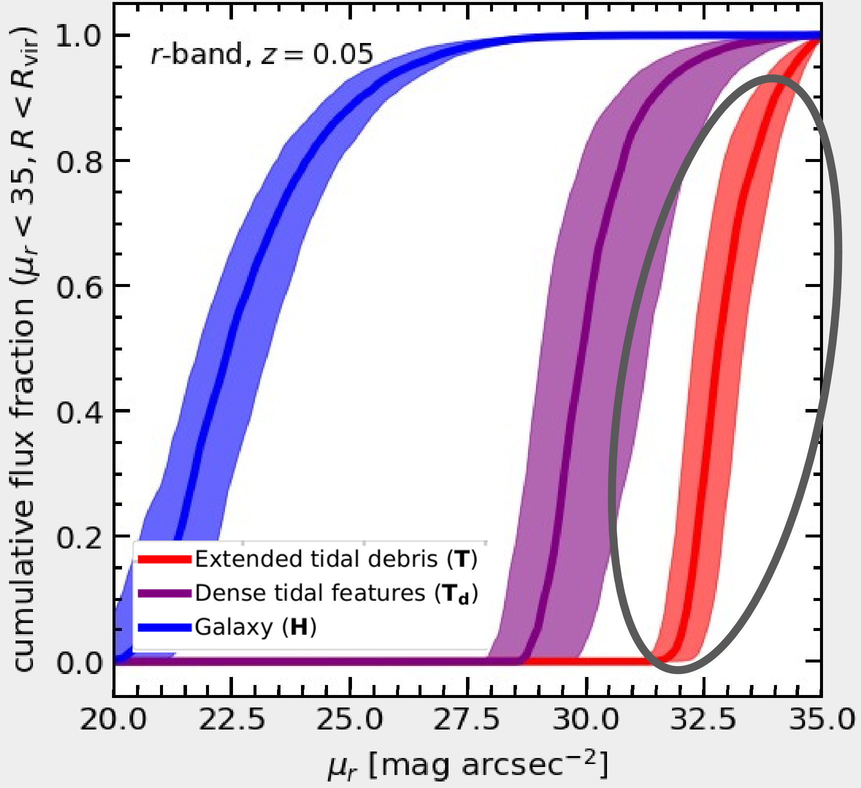

- SB limit of 30.5 mag / sq. arcsec is sufficient to recover over half the flux within tidal features

- Very diffuse light in the stellar halo is inaccessible (without binning) at expected LSST SB limits
  - It accounts for 25% of the total halo light on average

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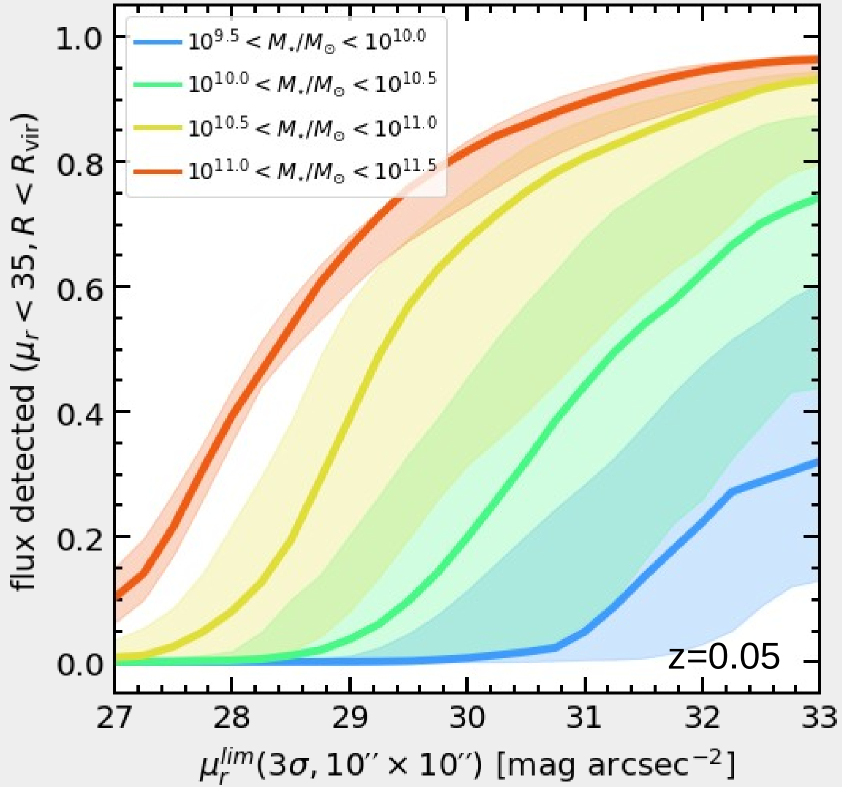

- In the nearby Universe (z~0.05), lower mass galaxies ($M_*/M_\odot<10^{10}$) remain unlikely to host detectable tidal features at Rubin Observatory 10-year depth.

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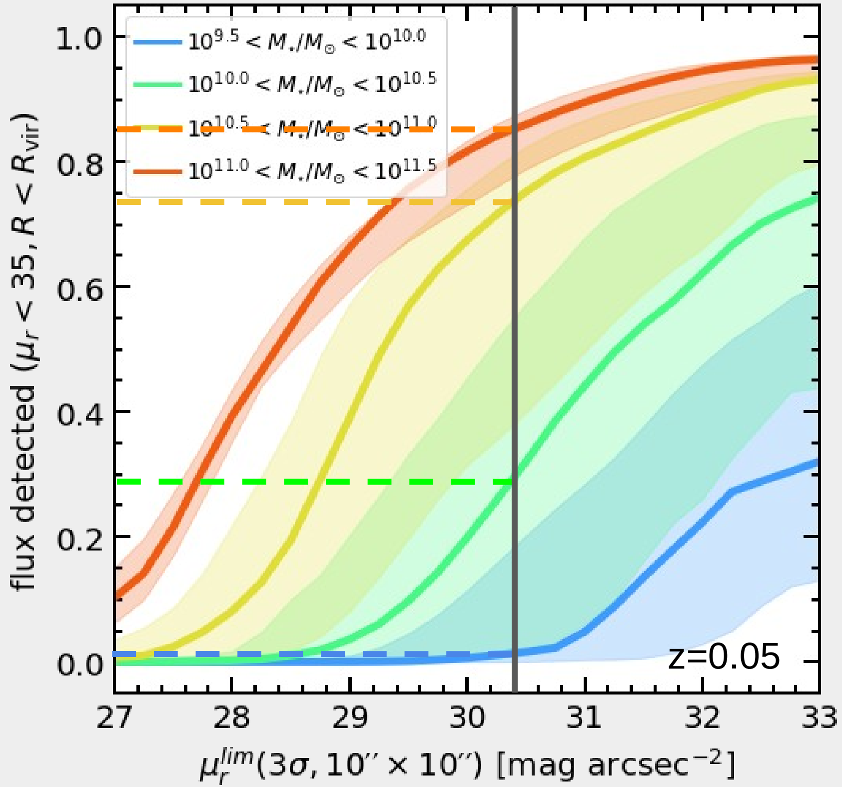

- In the nearby Universe ($z\sim0.05$), lower mass galaxies ($M_*/M_\odot<10^{10}$) remain unlikely to host detectable tidal features at Rubin Observatory 10-year depth.
- But a majority of massive galaxies host tidal features with detectable flux at 10-year depth
    - 80% in MW mass galaxies or 60% with a more conservative 29.5 mag arcsec^{-2} cut

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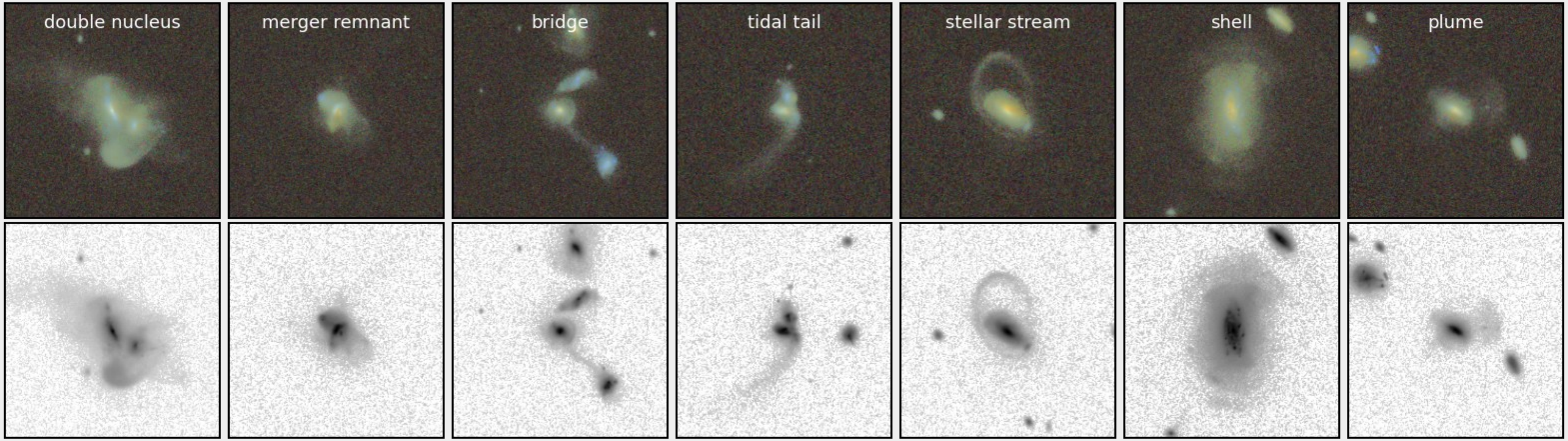
Visually classifying LSB features in the stellar halo

- ~50 volunteers visually classified tidal features mock Rubin Observatory images
  - Varied limiting surface brightness (single visit → 10 year depth)
  - Varied orientations



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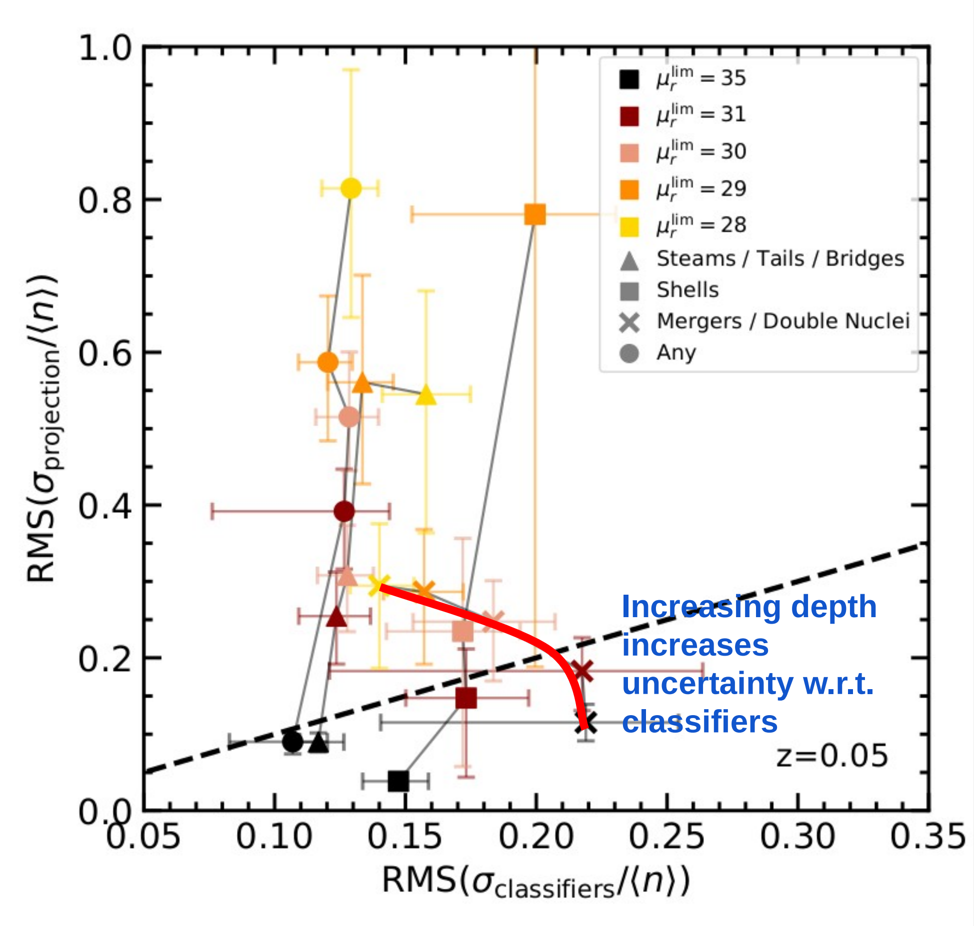
Visually classifying LSB features in the stellar halo

In most cases, deeper imaging means classifiers and more likely to agree with each other and between classifiers and for different projections of the same object

In some cases INCREASING the depth makes classification MORE AMBIGUOUS

- **As depth improves, morphologies can become more complex, introducing uncertainty in precise characterisation**

Due to significant disagreement between human classifiers there is a clear need to automate the detection and measurement of tidal features



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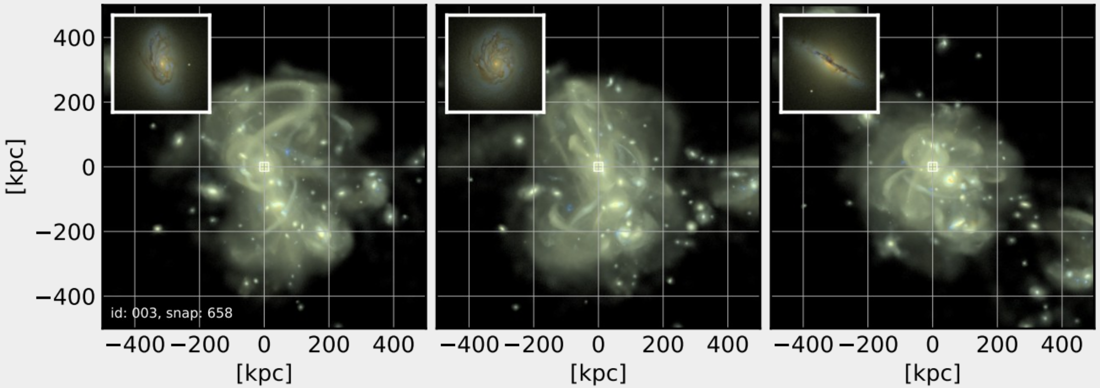
Visually classifying LSB features in the stellar halo

- Sources of uncertainty
  - Limiting surface brightness
  - Orientation
  - Chance projection of other objects
  - General ambiguity in tidal feature classification



Same galaxy in different projections

Conclusions and future plans

Conclusions

- After its 10 year survey, LSST will have sufficient depth to resolve a significant fraction of the flux found in tidal substructures of MW galaxy stellar haloes
- Around 75% of flux lies in these denser tidal features rather than more diffuse tidal debris which lie beyond the surface brightness limits accessible to LSST
- At sufficient depth, almost 100% of galaxies ($M_*/M_\odot<10^{9.5}$) possess tidal features
- Surface brightness limits, galaxy orientation, redshift, etc. have a clear effect on the ability of expert classifiers to visually identify and characterise tidal features
- Concurrence between classifiers generally improves with deeper imaging but morphologies can become more complex, introducing uncertainty in precise characterisation

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Contact: garrethmartin@kasi.re.kr

Future work: Challenges

- Extreme data volumes:
    - Billions of objects, significant computational challenges

- Costly data processing:
    - Existing data processing methodologies are intractable
    - New methods needed for identifying and characterising sub-structures

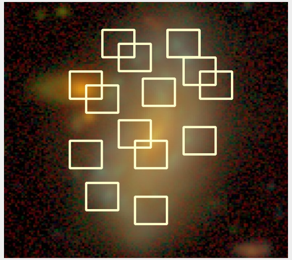
- Unfamiliar / unexplored discovery space:
    - Poorly understood biases
    - Unknown underlying populations
    - No existing large datasets to test new techniques

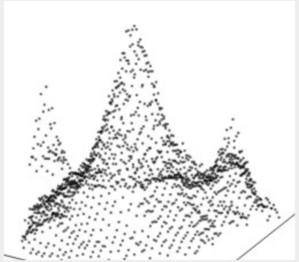
- Issues with interpretation of data
    - Robust comparison with theoretical predictions
    - Linking observed quantities to physical properties

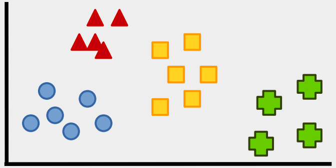
Without addressing the data challenges present in datasets like Rubin's, much of the potential of these facilities and much of the effort put into them by the scientific community will be wasted.

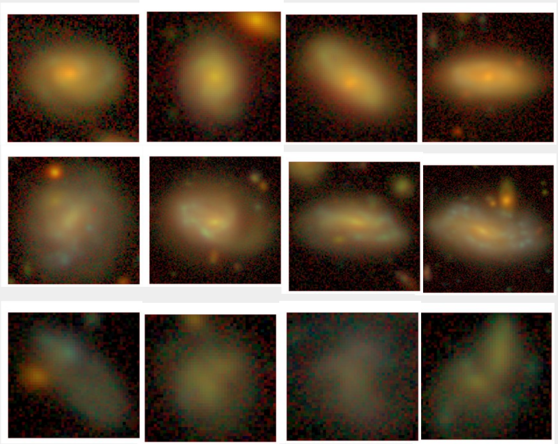
Martin+2020, MNRAS, 491, 1, pp.1408-1426, arXiv:1909.10537

Future work: Characterisation and detection of sub-structures









Developing tools for rapid classification and segmentation of tidal sub-structures building on novel unsupervised machine learning framework with PhD student Ilin Lazar (Hertfordshire).

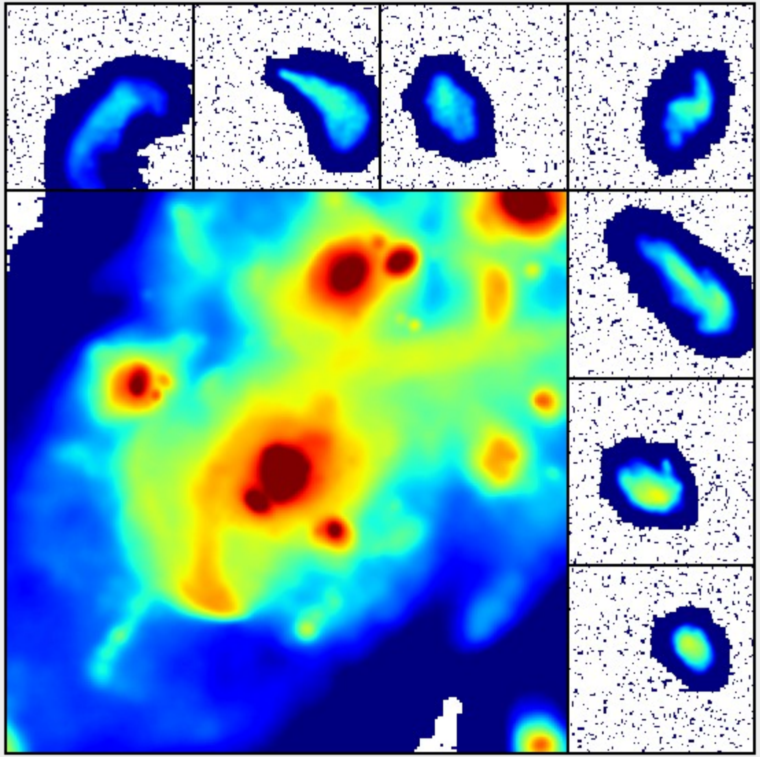
Internal description of each object can be efficiently mapped onto a library of similar components to quickly identify sub-structures (See Martin+2020)

The entire area of LSST can now be completed in around one week using 200 cores.

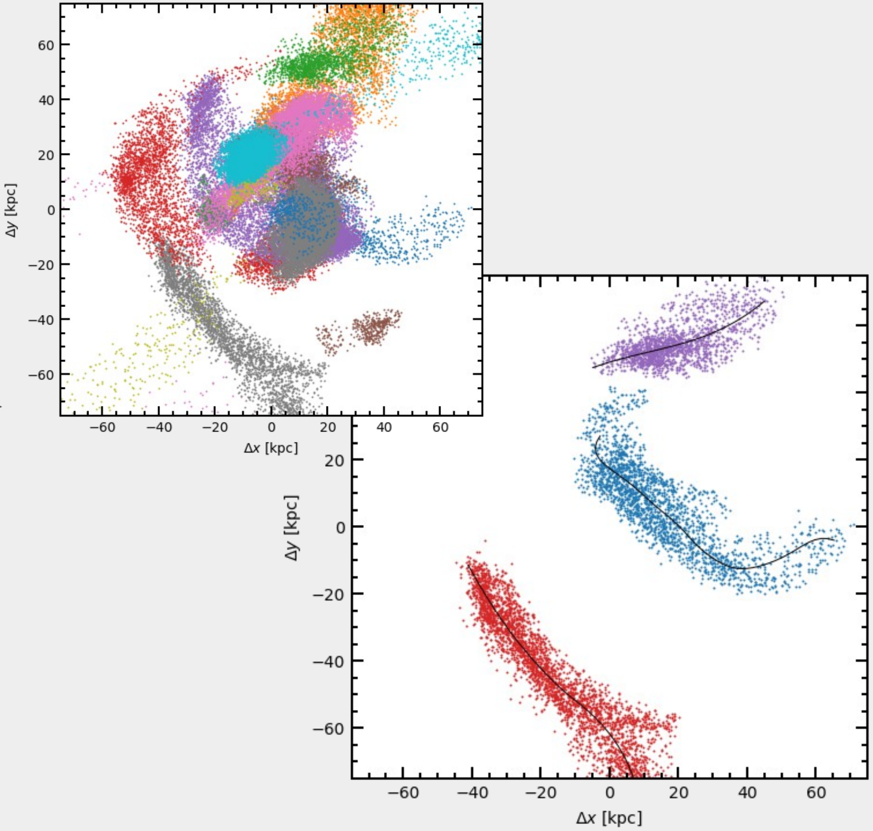
Martin+ in prep

Future work: automatic identification and measurement of tidal features

6-D Kinematically coherent features identified using clustering hierarchical density-based clustering (HDBSCAN, **McInnes+2017**)



Measure properties of individual tidal features along the medial spine of each tidal feature



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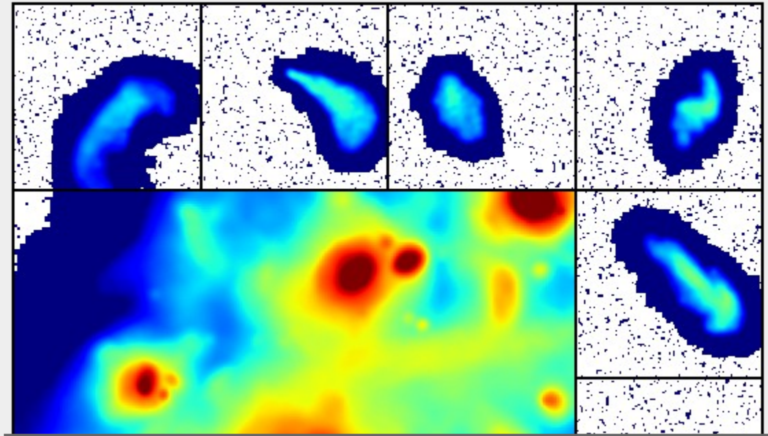

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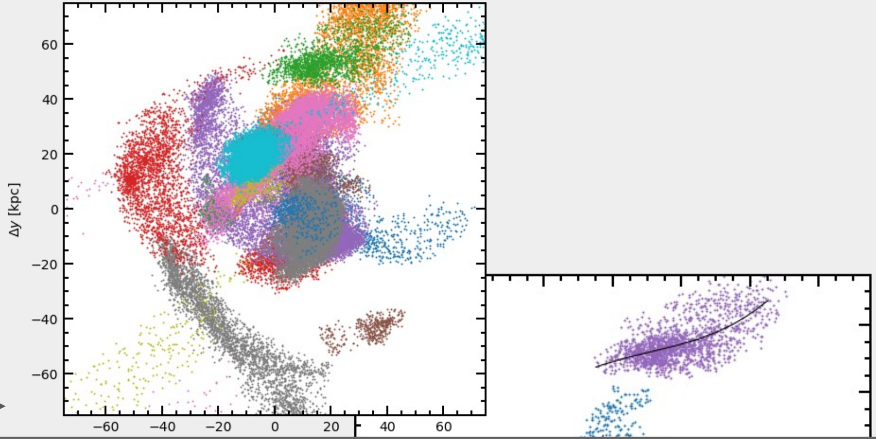

Comparison of 3-d measurements with recovered projected properties to account for projection and imaging depth biases.

Synthetic properties of sub-structures can then be connected with observed counterparts, allowing recovery of physical properties of their satellite galaxy progenitors.

<u>Develop a framework to recover robust assembly histories for observed galaxies.</u>

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Future work

Develop methods to automatically characterise and segment tidal features

Directly compare automated measurements of simulated tidal features with observed ones

> Expected frequency and distribution of tidal features as a function of surface brightness
>
> Expected distribution of tidal feature properties – length, curvature, colour etc.
>
> Statistical properties of tidal tails can provide a possible test of cosmological models (e.g. Ren+2020)

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